Proton Radiation Damage in P-Channel CCDs Fabricated on High-Resistivity Silicon

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***Abstract*—P-channel backside illuminated silicon charge-coupled devices (CCDs) were developed and fabricated on high-resistivity n-type silicon. The devices have been exposed up to 1×10^{11} protons/cm^2 at 12 MeV. The charge transfer efficiency and dark current were measured as a function of radiation dose. These CCDs were found to be significantly more radiation tolerant than conventional n-channel devices. This could prove to be a major benefit for space missions of long duration.**

***Index Terms*—Charge-coupled device (CCD), high-resistivity silicon, radiation damage.**

I. Introduction

UNIQUE charge-coupled devices (CCDs) have been developed at Lawrence Berkeley National Laboratory (LBNL) using high-resistivity n-type silicon and boron implants to create p-channel devices. Such devices are expected to be more radiation tolerant than standard CCDs since they are manufactured using the same high-purity n-type substrate used in the production of radiation detectors for high-energy physics experiments. While standard CCDs are manufactured on low- resistivity p-type silicon with typical depletion depths of several micrometers [1], our CCDs allow the application of an external voltage to create a depletion zone of 300 μm or more in the high- resistivity n-type substrate [2].

This thicker depletion region has a twofold advantage. One, near-infrared photons have a greater probability of being absorbed. Two, blue response can be extended via backside illumination while maintaining a robust 300-μm thickness. This is unlike conventional CCDs that require thinning to tens of micrometers to minimize field-free collection regions.

II. Radiation Damage

Proton irradiation generates displacement damage in the silicon. Midgap levels in the depletion region will contribute to the dark current. Since our CCDs have a much larger depleted volume, a concern existed that unacceptable dark current levels might result from radiation damage.

Traps in the channel region capture charge carriers during readout and degrade the charge transfer efficiency (CTE). The number of such traps is a function of occupied channel volume, and as such is independent of the depletion depth, so thicker CCDs do not have a disadvantage here. An additional narrow channel implant increases the charge density for small charge packets and thereby improves the CTE [3]. Large charge packets that fill the entire well cannot benefit from this improvement.

Conventional n-channel CCDs have a phosphorus-doped buried channel and suffer from the generation of phosphorus-vacancy (P-V) electron traps that degrade charge transfer efficiency [4]. As pointed out by Spratt *et al.* [5] and Hopkinson [6], the dominant hole trap expected after proton irradiation of a p-channel CCD is the divacancy. Divacancy formation is considered to be less favorable in a p-channel CCD than P-V formation in an n-channel CCD. In addition, the energy level of the divacancy, 0.21 eV above the valance band, is not likely to yield efficient dark current generation sites when compared to P-V sites, located closer to the middle of the bandgap (0.42–0.46 eV below the conduction band edge [4], [5]).

Fabrication of the CCD on high-resistivity silicon is expected to enhance the hardness to P-V-generated dark current given the extremely low phosphorus concentration in the bulk (low to mid 10^{11} cm^{-3}). For these reasons, it is expected that p-channel CCDs will be more resistant to proton damage than their n-channel counterparts. However, other hole traps are possible (e.g., interstitial carbon [7]) and are under investigation for possible deleterious effects on p-channel CCDs.

III. Measurements

For the work reported in this paper, two sets of four CCDs were characterized and then irradiated with protons at the LBNL 88-in Cyclotron. One set employed an additional "notch" implant in the channel. A proton energy of 12 MeV was chosen to yield a high nonionizing energy loss (NIEL), giving the greatest damage at the lowest radiation dose, while maintaining sufficient penetration depth to spread out the damage evenly over the device thickness. The dose can easily be scaled to other proton energies using the National Institute for Science and Technology PSTAR data.[1]

The devices are 512 by 1024 pixels, 15 μm pitch, engineering-grade devices. They have not been backside processed, are 600 μm thick, and therefore cannot be fully depleted. A substrate bias voltage of 40 V was chosen, generating a depletion region of about 300 μm. Accordingly, they are used as front illuminated devices. The four CCDs from each set were irradiated at doses of 5×10^9, 1×10^{10}, 5×10^{10}, and 1×10^{11} protons/cm^2. The irradiation took place while the

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[1]See http://physics.nist.gov/PhysRefData/Star/Text/contents.html

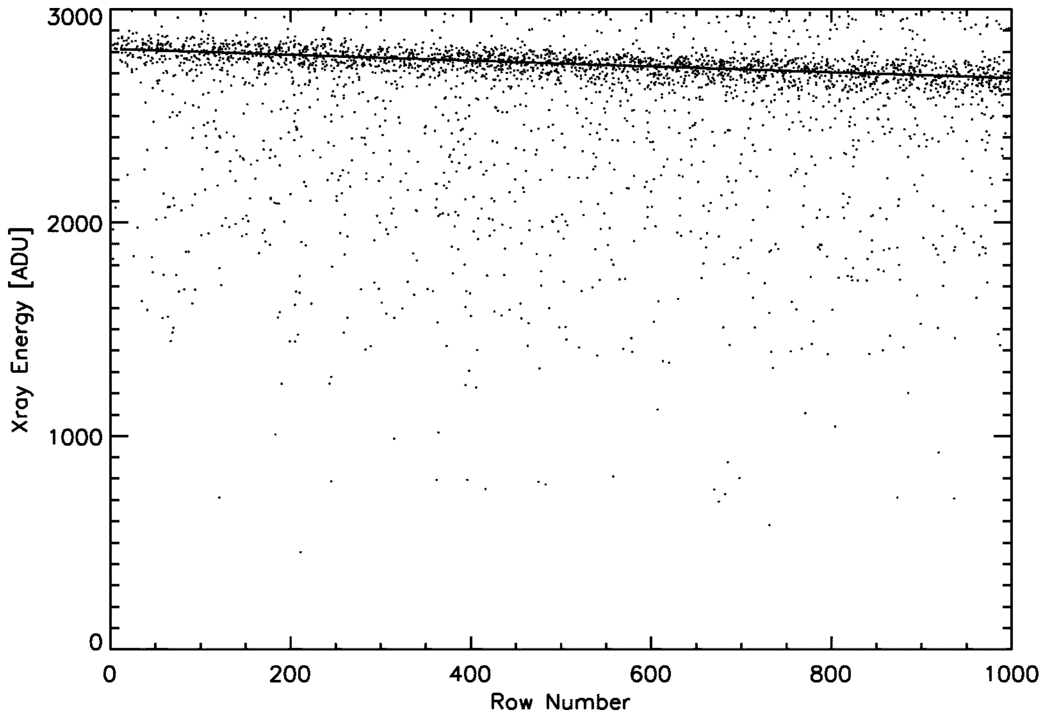

Fig. 1. X-ray stacking plot for parallel CTE calculation. The points clustered around the line show the ^{55} Fe kα X-ray. the slope is a measure of the CTE at 128 K. The measurement was performed after a dose of 1×10^{10} protons/cm^2.

devices were unpowered and at room temperature. The devices were characterized before and after irradiation to evaluate the performance degradation due to radiation damage.

IV. CTE Degradation

The CTE is the most critical functional parameter of the CCD affected by radiation. CTE is defined as the fraction of charge that is successfully transferred from one pixel to the next during readout. This means that the charge readout is

$$Q_{\rm out} = Q_{\rm dep} \times {\rm CTE}^{n_{\rm pixel}} \tag{1}$$

where $Q_{\rm dep}$ is the charge deposited in a pixel and $n_{\rm pixel}$ is the number of transfers before the pixel is read out. CTE is separated into the horizontal component $\mathrm{CTE}_{\rm serial}$ and the vertical component $\mathrm{CTE}_{\rm parallel}$.

Previous space-based devices suffered from poor CTE due to radiation damage. This effectively limits CCD size, thereby increasing the parts count and complexity for large mosaic cameras. The goal is to produce a class of CCDs that can maintain a good CTE over years in space.

A. CTE Extraction

Even though the above definition seems intuitive, methods for CTE measurement can give different results since the CTE is a function of temperature, readout speed, signal size, background signal, and clocking waveform. CTE is measured here using a ^{55}Fe X-ray source, which deposits on average 1620 e$^-$ per hit pixel [1]. By plotting the peak height versus the distance along the serial register or row number, the serial CTE and parallel CTE can easily be found (see Fig. 1).

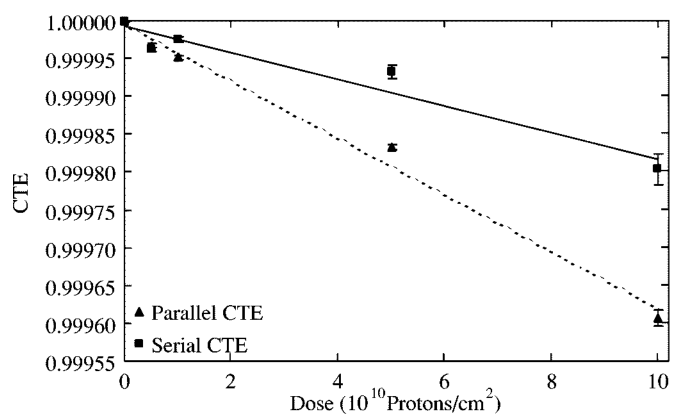

Fig. 2. The CTE degradation at 128 K after irradiation.

B. CTE Results

CTE is measured as a function of temperature with a 30-kpixel/s readout rate and an X-ray density of roughly 1/70 per pixel. Fig. 2 shows the CTE as a function of radiation dose at 128 K. This temperature was chosen since it appears to be optimal for this type of CCD at this readout speed. The CTE of the devices was 0.999 999 before irradiation. Errors in the CTE are dominated by the error in the fit to the peak height stacking plot. A reduction in CTE in one direction smears out the peak in the other direction, increasing the fit errors. The error is estimated to be

$$\Delta {\rm CTE}_{\rm serial} = 10^{-6} + (1 - {\rm CTE}_{\rm parallel})/20 \tag{2}$$

$$\Delta {\rm CTE}_{\rm parallel} = 10^{-6} + (1 - {\rm CTE}_{\rm serial})/20. \tag{3}$$

Since each device was irradiated to a specific dose, there is the opportunity to observe annealing effects and to perform ad-

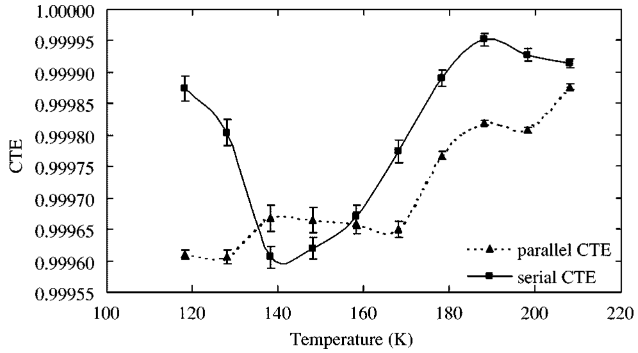

Fig. 3. The CTE as a function of temperature for the CCD with the highest dose (1×10^{11} protons/cm^2).

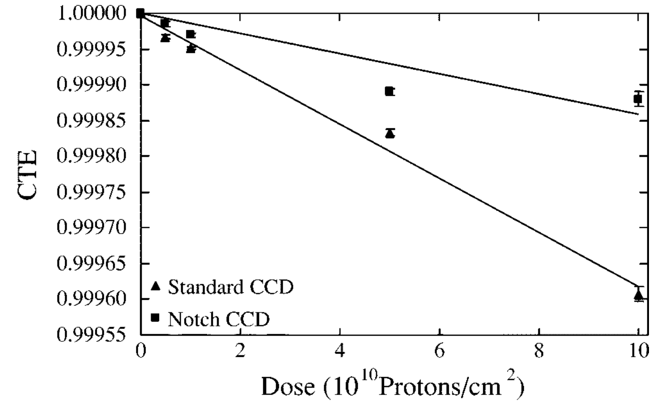

Fig. 4. Comparison of parallel CTE of devices with and without notch at 128 K.

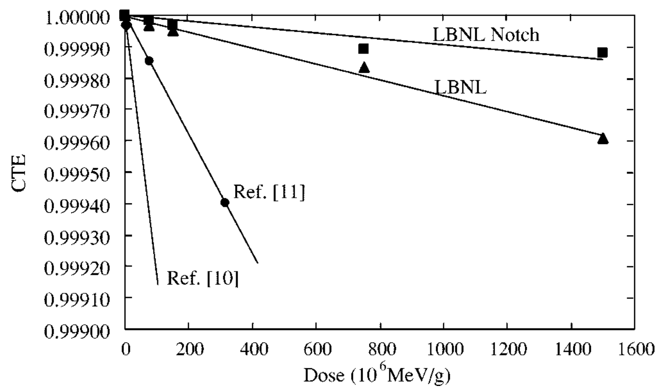

Fig. 5. Comparison of CTE degradation for LBNL and modern n-channel CCDs. Linear fit lines have been added to facilitate comparisons.

ditional measurements on any device at a later date. However, no insight is gained into the natural variation of the radiation tolerance from observing multiple devices with the same dose. A future irradiation run is planned to bring all devices to a common total dose. One can then look at the inherent device variation and estimate the spread in CTE at different radiation levels.

At 128 K, serial CTE is less affected by the radiation since traps in the serial register are often filled by losses from a preceding X-ray. The slower parallel line shift does not benefit from the X-ray density.

Fig. 3 is an example of the temperature dependence of the CTE. The CCD with the highest radiation dose was chosen since the features in the plot are most pronounced. Data at lower doses show less pronounced minima at the same temperature. The serial CTE data are more interesting. They show the inefficiency of the traps at high temperature, where the clock overlap time is longer than the detrapping time, as well as the low-temperature region where the traps are mostly saturated due to the long detrapping time [8]. The parallel CTE does not recover at cold temperatures since trap saturation does not play a role for the much slower line transfer over the operating temperature range of the CCD. This could be different for higher frame-rate readout.

C. The "Notch" Implant

The CCDs with the "notch" implant are identical by fabrication to the other set of CCDs except for an additional boron implant that shapes the potential well in the vertical channels to create a narrow notch along the center of the channel. The horizontal register on both sets of CCDs has a notch implant, scaled wider to allow summation of multiple pixels. Fig. 4 shows the parallel CTE of the regular and notch devices. The notch devices show a radiation tolerance that is more than twice as good as that of our regular CCDs. This is to be expected since the notch implant occupies roughly 1/2 the width of the regular channel and all of our test charges reside in the notch. Thus they are exposed to only half the radiation damage.

D. Comparison With Conventional Devices

In the literature, there are only a limited number of rigorous measurements of CTE degradation due to radiation damage that use low temperature and similar speed CCDs and do not use a background charge to improve CTE. Two good examples are [9] and [10]. Unfortunately, the proton energies chosen are very different. The energy deposited in the silicon by protons can be separated into ionizing and nonionizing energy loss. To compare the damage to the silicon, the NIEL dose is compared [8]. In Fig. 5, the four different CCD types are compared. Since the data from [9] and [10] do not include higher radiation doses, the linear fit lines have been extended as an extrapolation. From the slope of the lines, the shift in CTE is calculated and

$$\Delta\mathrm{CTE} = 8.3 \times 10^{-12}\ \mathrm{g/MeV} \tag{4}$$

is found for the data from [9]

$$\Delta\mathrm{CTE} = 1.9 \times 10^{-12}\ \mathrm{g/MeV} \tag{5}$$

is found for the data from [10], while only

$$\Delta\mathrm{CTE} = 2.5 \times 10^{-13}\ \mathrm{g/MeV} \tag{6}$$

is observed for our standard high-resistivity devices and

$$\Delta\mathrm{CTE} = 9.6 \times 10^{-14}\ \mathrm{g/MeV} \tag{7}$$

for our notch high-resistivity devices.

A three-year high-earth-orbit space mission can expect 2×10^7 MeV/g of NIEL. This would cause a CTE degradation of only 1.9×10^{-6} in one of our notch devices. While it is clear that high-resistivity p-channel CCDs are much more radiation tolerant than conventional devices, the orders of magnitude difference in irradiation doses in the measurements make a direct comparison difficult. Since a much higher radiation tolerance is expected in our case, the experimental data are focused at much higher doses, and comparison to low dose data is problematic.

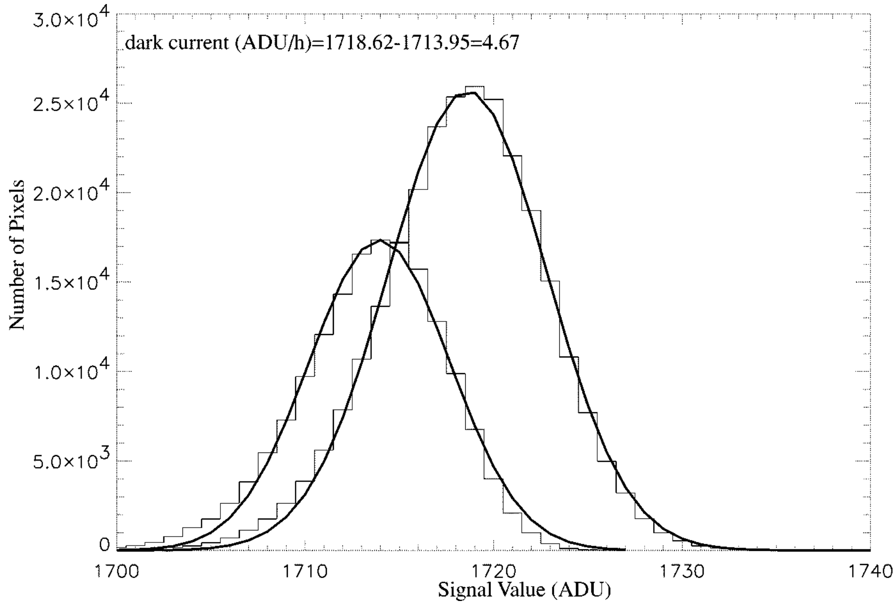

Fig. 6. Typical histogram for dark current calculation. The data to the right are from the pixel area; the data to the left are from the serial overscan area.

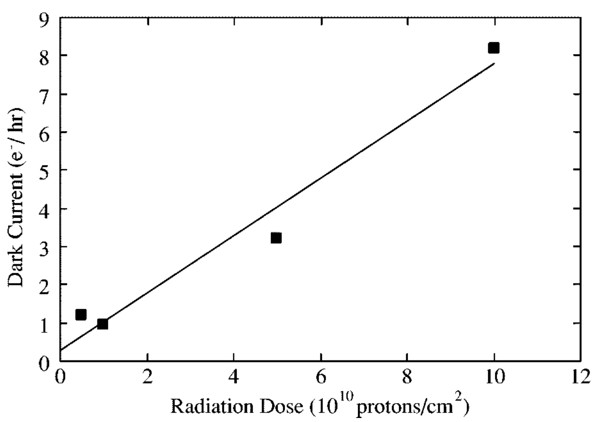

Fig. 7. Dark current in electrons per pixel per hour versus radiation dose at 128 K. The line is a linear fit to the data.

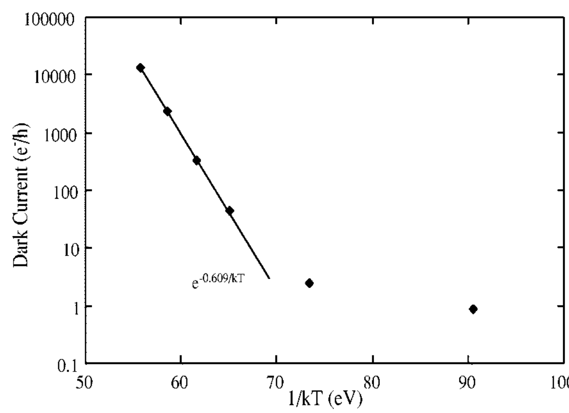

Fig. 8. Dark current versus 1/kT after a radiation dose of 5×10^9 protons/cm^2. The measurements are connected with a line to guide the eye. An exponential fit to the four highest dark current points yields an activation energy of 0.609 eV for that region.

V. Dark Current

To measure the dark current accurately at low temperature, multiple 1-h dark exposures were taken. By assigning each pixel the minimum value read in any of the frames, sporadic events such as cosmic rays are eliminated, while CCD parameters such as dark current and hot pixels are retained. The dark current is then calculated by fitting a Gaussian to the histogram of all pixel values in the image area and another Gaussian to the histogram of all pixel values in the serial overscan area. The difference in the location of the peaks is the dark current observed during 1 h (see Fig. 6).

Fig. 7 shows the measured increase of dark current with radiation dose at one fixed temperature. The detrimental effect of dark current is that the added shot noise cannot be eliminated from the image. The minimum read noise of the tested CCDs is 2 e^-. Therefore, dark current of less than 4 e^-/exposure has little impact on the CCD performance. Even after the highest irradiation dose, 30-min exposures meet that benchmark.

The dark current is strongly dependent on the temperature [1]. Fig. 8 shows the typical exponential increase of dark current with temperature, as well as the low-temperature limit. An exponential fit to the four high-temperature points yields an activation energy of 0.609 eV for the midgap levels responsible for the dark current generation. Even after the moderate radiation dose (5×10^9 protons/cm^2) of the CCD in Fig. 8, the dark current is not significantly elevated.

VI. Conclusion

The high-resistivity p-channel CCDs exhibit extremely low dark current at the operating temperature. This is attributed to the ultra-high-purity silicon, the lower operating temperature, and a gettering process used for device fabrication. The dark current degradation due to radiation damage is small. Even after a dose of 1×10^{11} protons/cm^2, exposures up to 30 min are dominated by read noise.

The initial serial and parallel CTE of all tested devices was excellent over the entire operating temperature range. Radiation damage proved to be much less detrimental than in conventional CCDs. Both serial and parallel CTE are substantially more radiation tolerant to proton radiation exposure. The notch implant in the parallel register further improves the radiation tolerance of the parallel CTE. The potential lifetime in space is measured in decades, not years.

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